Photovoltaic (PV) Power Variability Modeling and Analysis Approaches

April 14, 2010

Joshua S Stein Ph.D.
Photovoltaic and Grid Integration Dept.
Sandia National Laboratories
(Email: jsstein@sandia.gov)

Utility Wind Integration Group: Solar Integration
Portland, OR

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company,
for the United States Department of Energy's National Nuclear Security Administration
under contract DE-AC04-94AL85000.

Problem Statement

- Solar integration studies will require credible PV and CSP power output estimates for systems that are:
  - diversely sized (kWs to MWs)
  - time-synchronous
  - sub-hourly (1-min?)
  - distributed unevenly across a region
- Developing a valid model of short-term, dynamic solar resource over a large area is the main challenge.
  - PV output is proportional to spatially averaged irradiance over the plant.

Validation Criteria

- How to judge irradiance/power model validity?
  - Comparison of historical measured irradiance and power to predicted values for same time periods
    - Clearness index distribution
    - Ramp rate distributions
    - Duration and magnitude of changes
    - Autocorrelation features
    - Spatial correlation features
    - More?
- How much accuracy is necessary?
  - Depends on intended application
    - Predicting vs. Forecasting

Prediction vs. Forecasting

- **Prediction**
  - Given low resolution, historical solar estimates (e.g., satellite data), predict 1-min PV plant performance for a fleet of different plants located across a balancing area or region.
  - Used for testing build-out scenarios
- **Forecasting**
  - Prediction of plant performance into the future.
    - Timing and magnitude of regional weather changes at a point or across a balancing area.
    - Location and velocity of fronts (step changes)
  - Used for operations planning

Clearness Index

- PV output is primarily a function of integrated insolation reaching the array.

- Clearness index (CI) removes predictable diurnal and seasonal cycles.

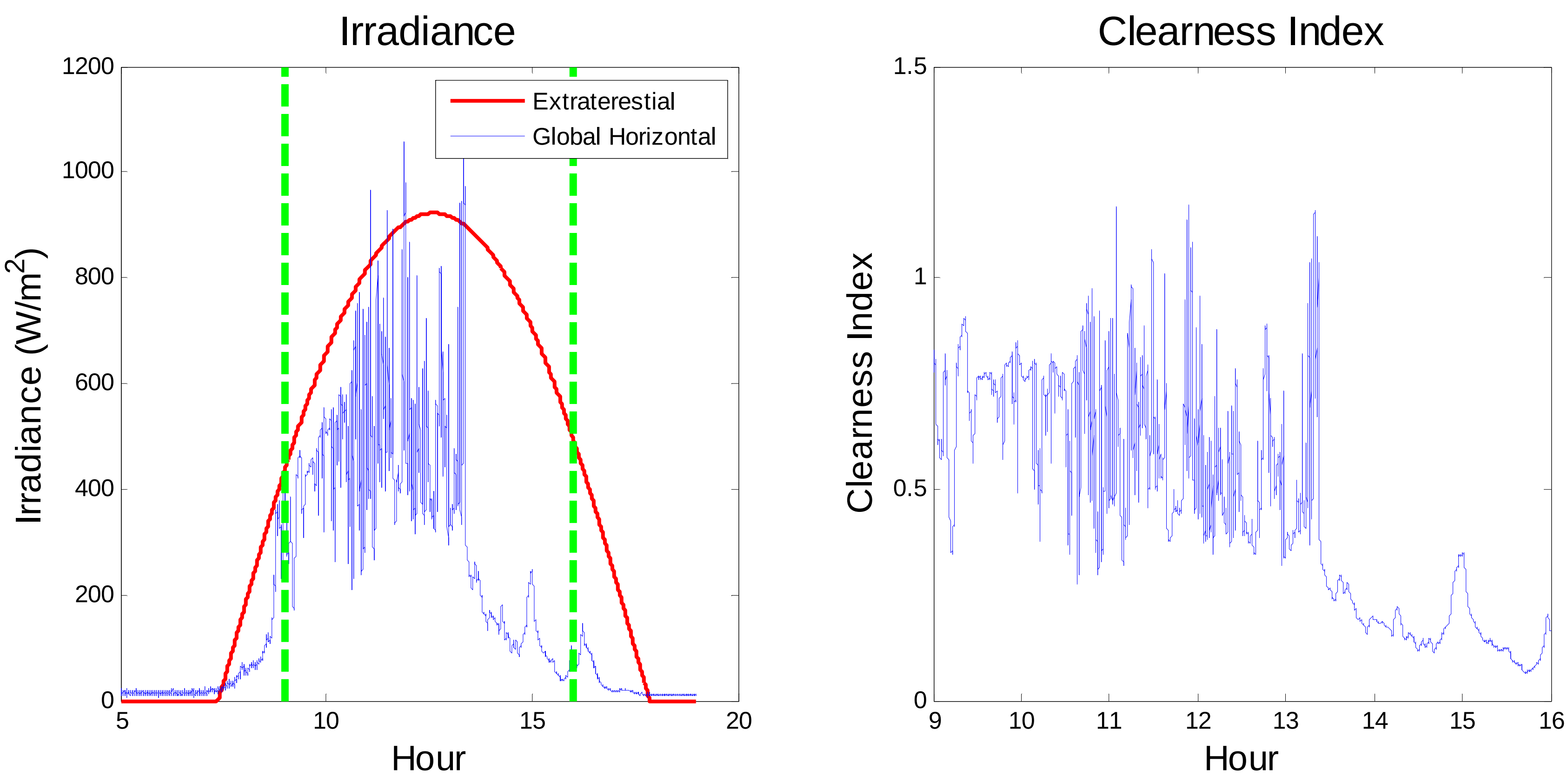
$$CI = E/E_a$$

E = global horizontal irradiance [W/m^2]

Ea = extraterrestrial irradiance * cosine(zenith angle) [W/m^2]

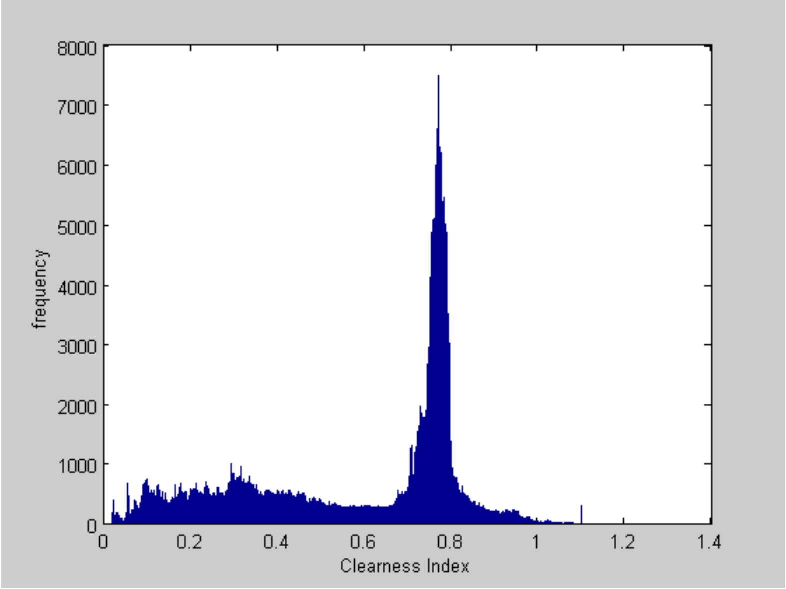
- Clearness index can be converted to irradiance

Clearness Index

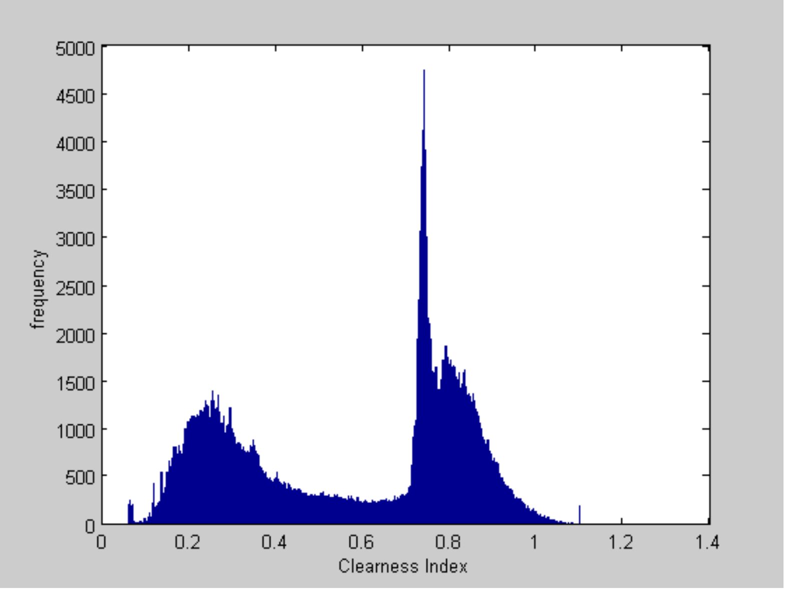


Properties of Clearness Index

- Short time interval measurements of CI exhibit bimodal distributions.
- Valid model should reproduce this pattern.



Florida (1 month)



Hawaii (1 month)

Sandia National Laboratories

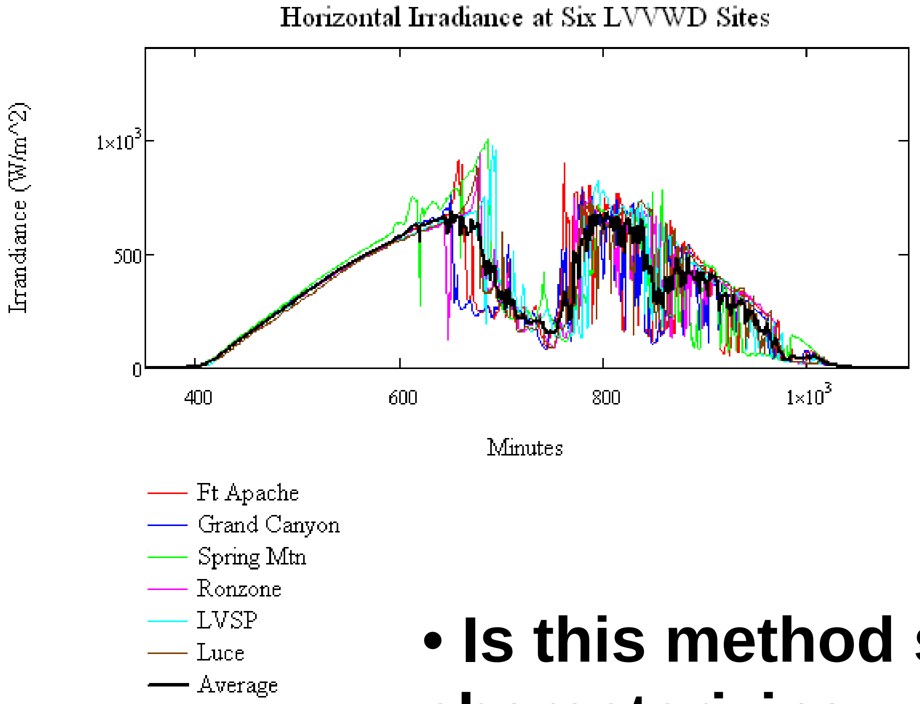
Ramp Rate Distributions (fixed time intervals)

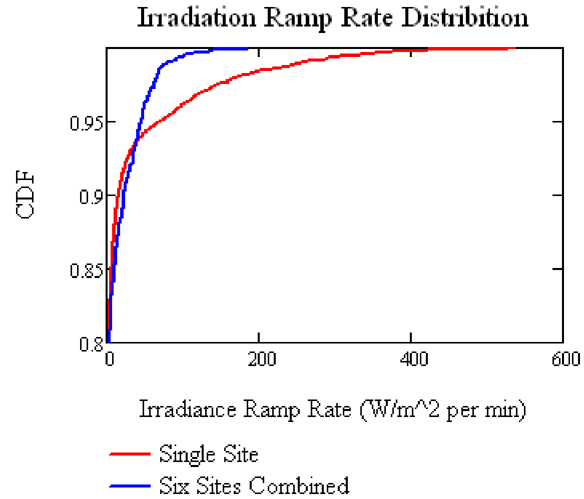
- Fixed time interval methods examine the distribution of irradiance and power changes ('ramps') over a fixed time interval (e.g., 1-sec, 1-min, 10-min, etc.)
  - Analysis of step changes
  - Analysis of moving averages
  - Regression of data within fixed time windows
- This has been a primary focus of PV variability studies.

Sandia National Laboratories

Ramp Rate Distributions (fixed time intervals)

- **Distribution of fixed time interval ramps provide information about the role of geographic diversity in reducing ramp rates.**



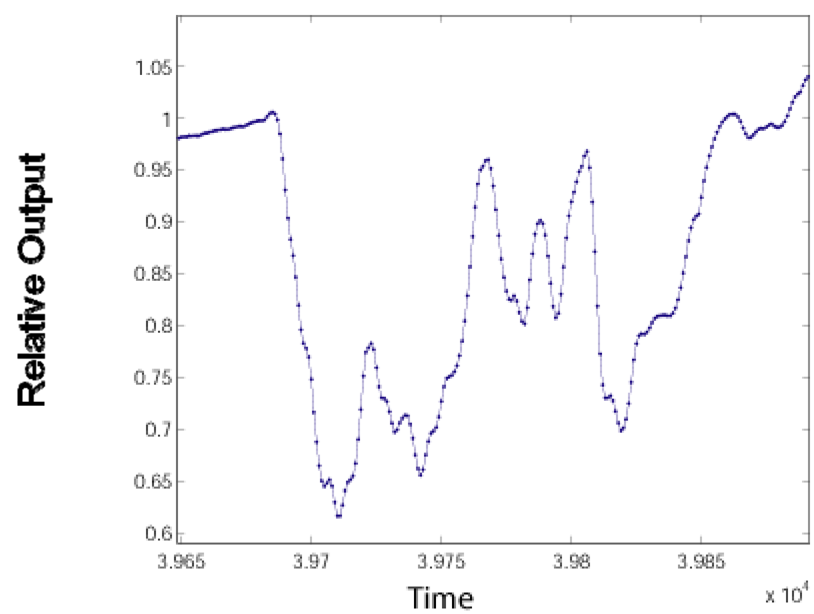


- **Is this method sufficient for characterizing variability?**

Sandia National Laboratories

Ramp Events with Flexible Time Intervals

- **Utilities want information about frequency of ramp durations and magnitude in order to manage reserves.**
  - **e.g., 1 min ramp rate might last for 20 minutes.**

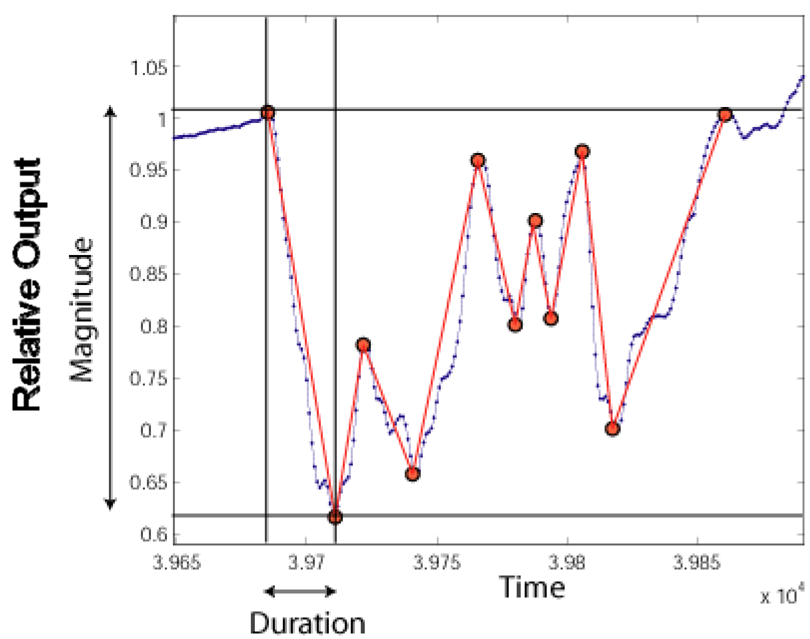


Sandia National Laboratories

Ramp Events with Flexible Time Intervals

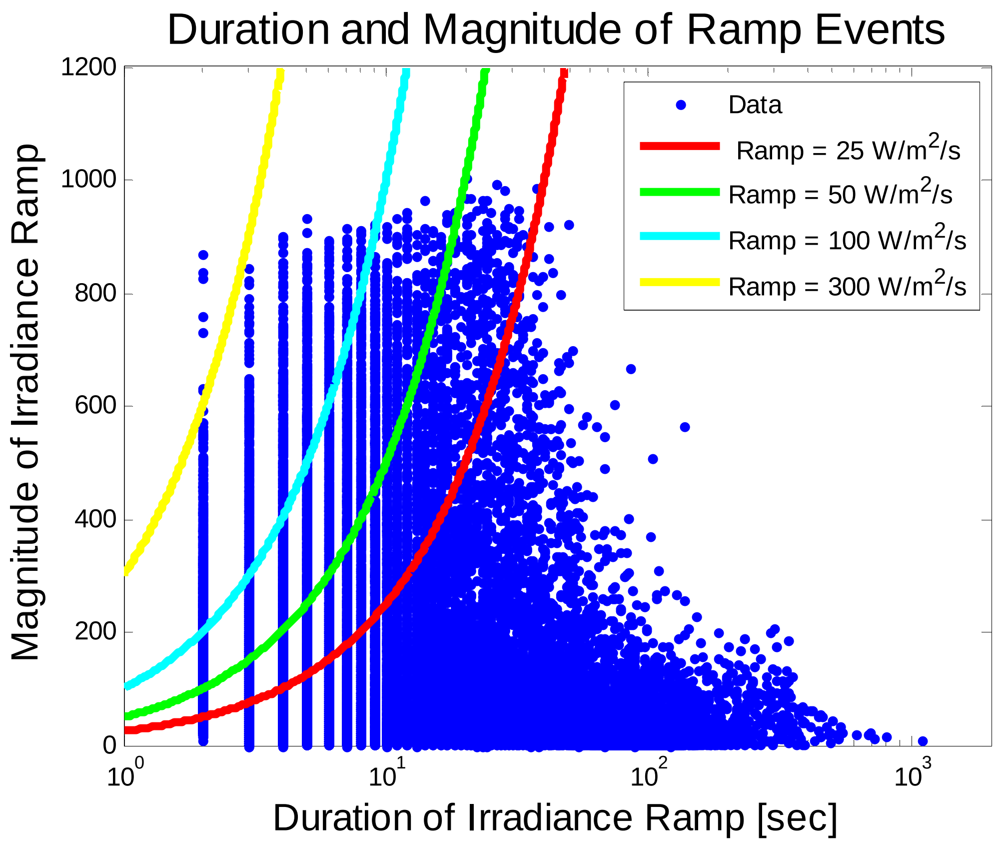
- **A piecewise linear approximation calculates 'significant' changes (e.g. Horst and Beichl, 1996 and many others).**
- **Results in a reduction of data and an increase in knowledge about the character of the changes.**

- **Ramp events are described by two of three variables:**
  1) **Magnitude (Δp)**
  2) **Duration (Δt)**
  3) **Rate = Δp / Δt**



Characterizing Flexible Time Ramp Events

- **Bivariate distribution (Duration and Magnitude)**
  - **1 month of 1-sec data from Hawaii (~37,000 ramps)**

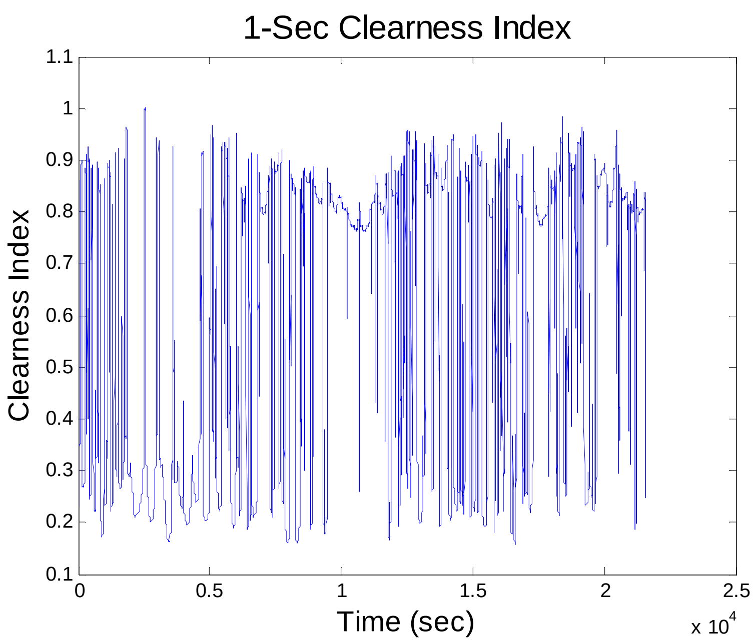


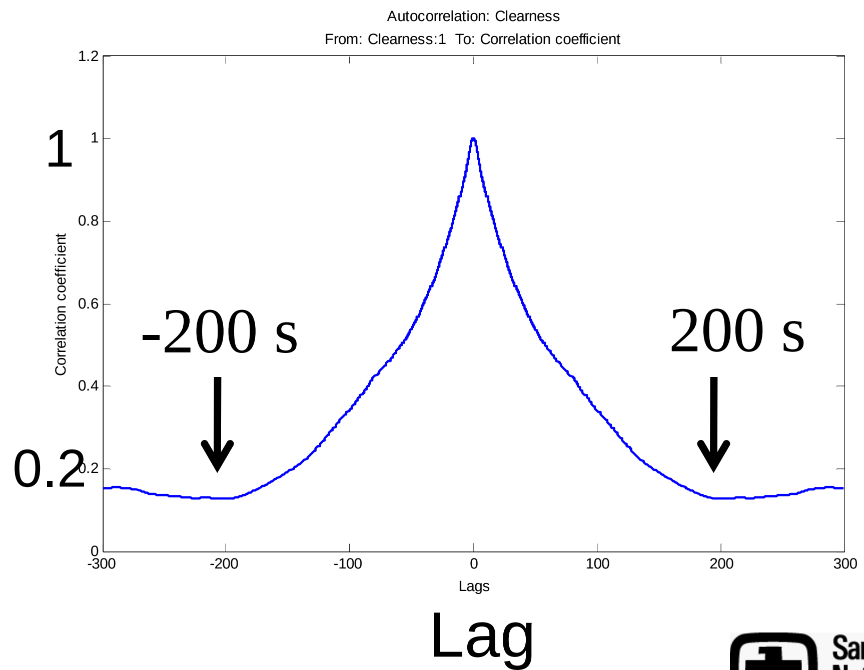
Autocorrelation

- Clearness indices exhibit autocorrelation features
  - Shadows extend over large areas and influence output for many time intervals.
  - Autocorrelation plots provide information about the combination of the size and spacing of shadows and the transit speed of the shadows across the ground.
- Shadow transit speed can be measured (and shadow size and spacing can be inferred)
  - Aviation weather
  - Irradiance sensor networks

Autocorrelation

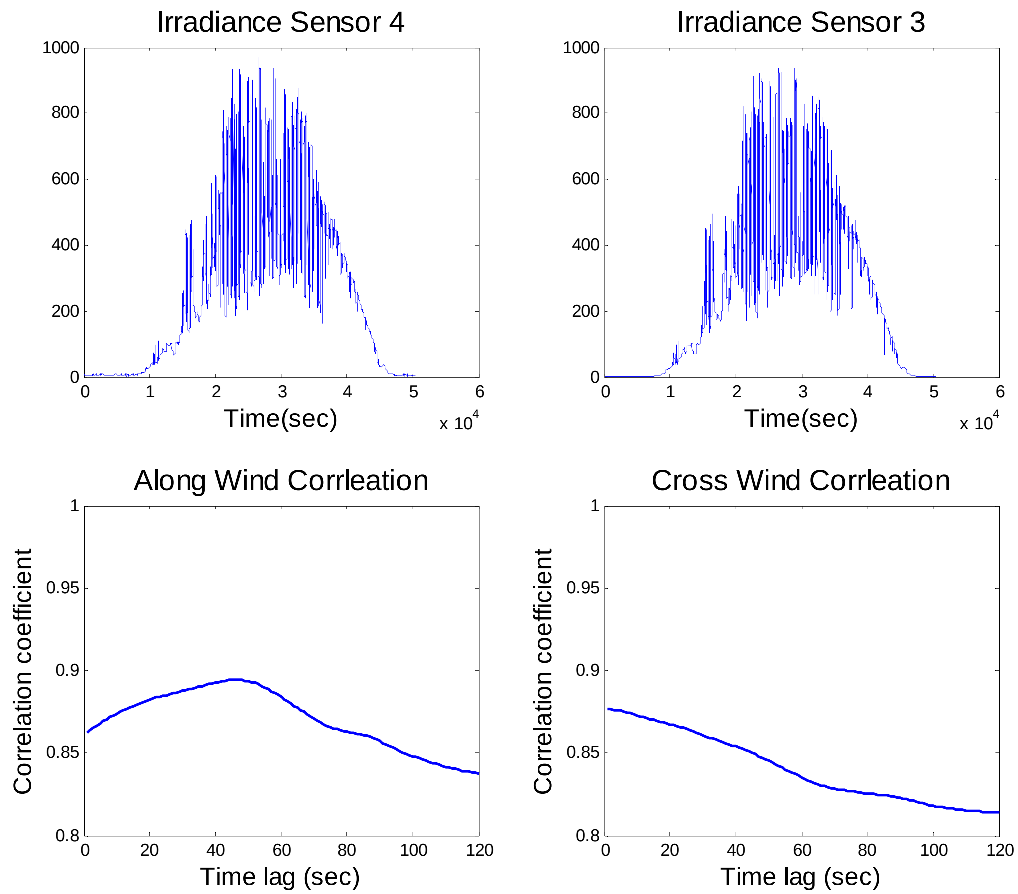
Autocorrelation plot reveals information about characteristic time scale between and inside shadows.





Spatial Correlation Features

- Irradiance (and power) measurements exhibit a spatially and temporally sensitive correlation.
- Cloud patterns can remain relatively static for some time (and distance).
- Autocorrelation features are directional and dependant upon cloud velocity patterns.



Proposed Modeling Approaches

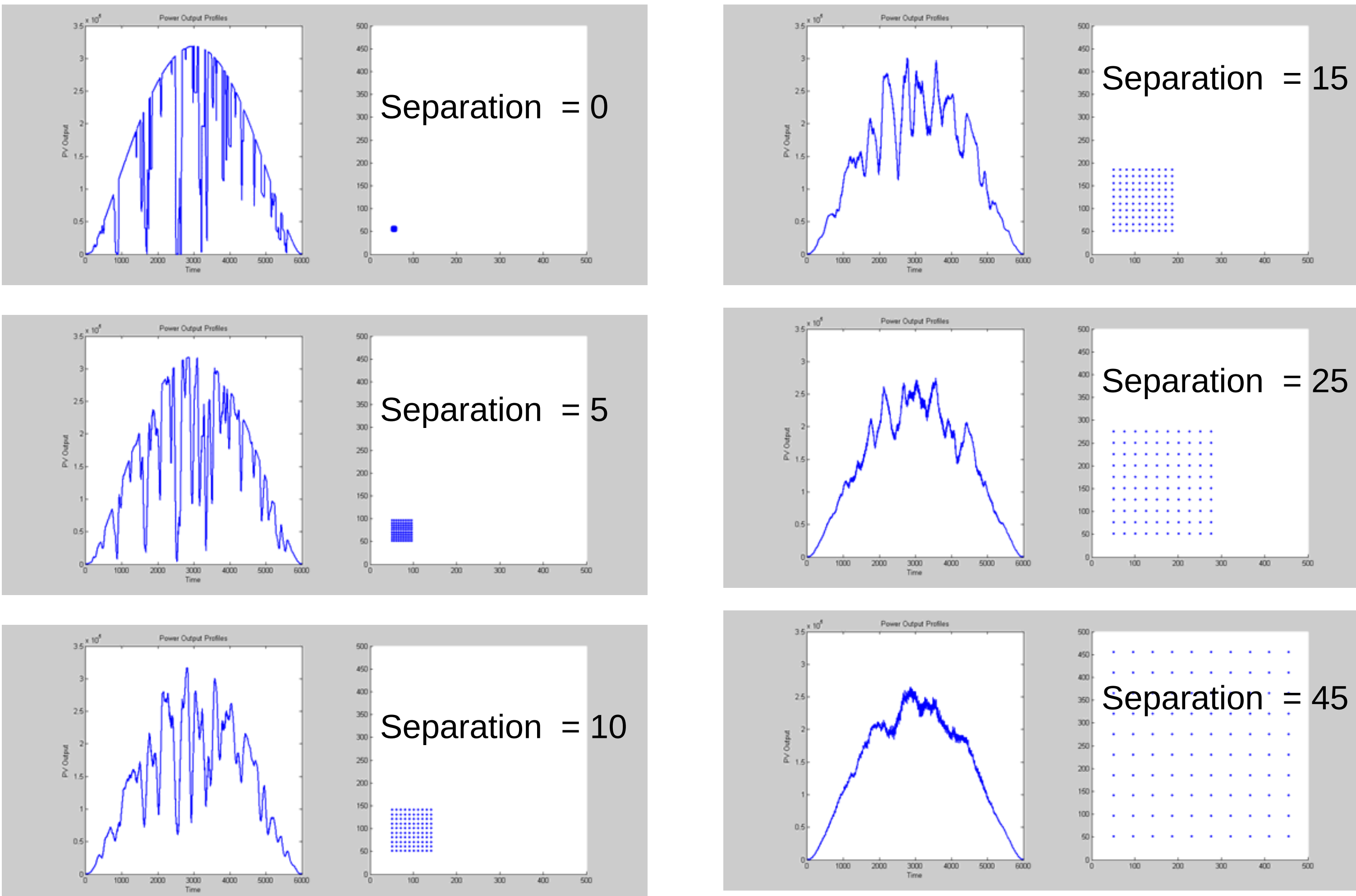
- Plant output is related to a moving average of point irradiance (Longhetto et al., 1989).
  - Assumptions include irradiance is simply time-shifted
  - Falls apart for large or distributed plants
- Hoff and Perez (2009) suggest that relative output variability follows a 1/sqrt(N) relationship.
  - Assumptions include identical PV systems, irradiance variability is the same everywhere, cloud patterns are the same everywhere.
- Autoregressive time series models
  - Glasbey (2000, 2008), Tovar et al. (several papers)
- Cloud (Sky) Simulators
  - Assumes that cloud fields can be predicted from available data (e.g., ground based weather or satellite)

Modeling Effect of Geographic Diversity with Simple Cloud Simulator

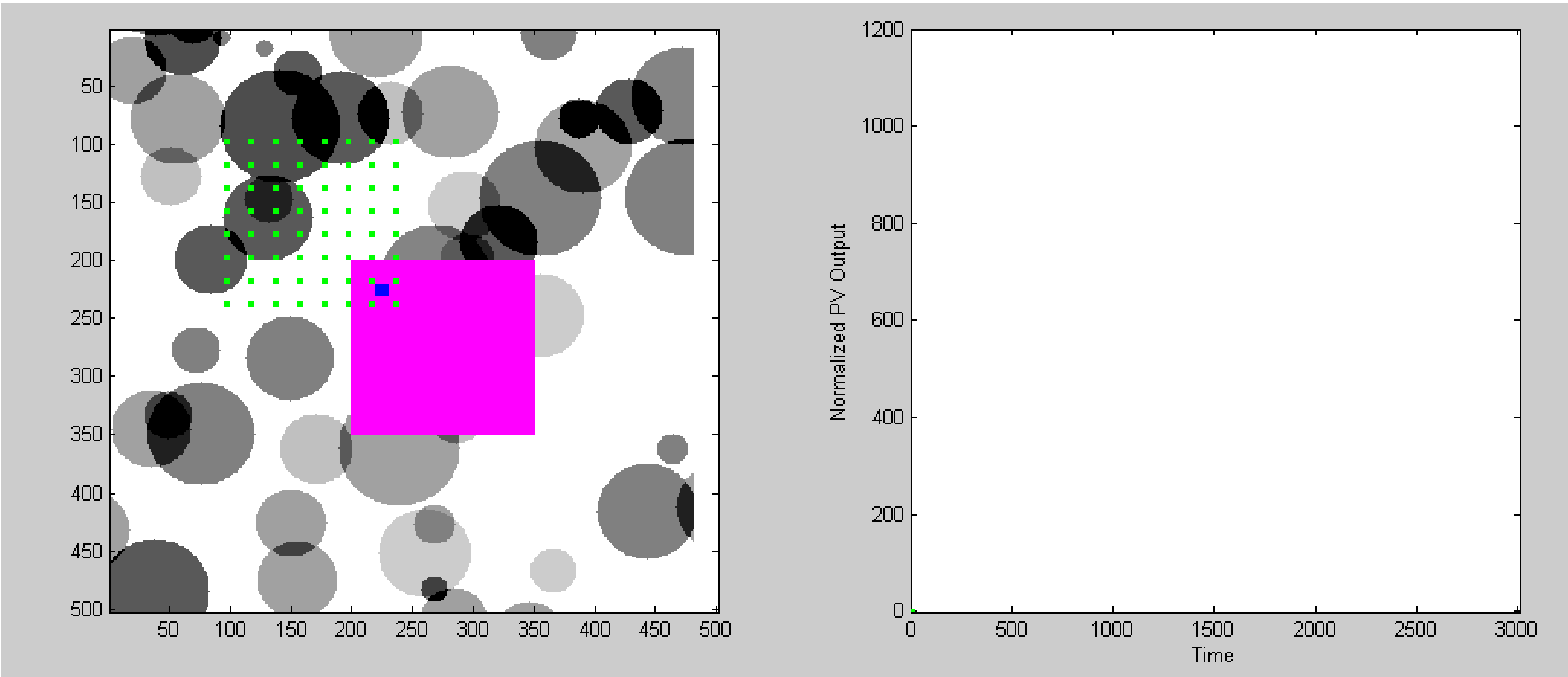
- **Synthetic cloud model**
  - Define cloud size range
  - Define cloud transmittance
  - Define cloud coverage
- **(1) Examine different spacing between plants**
  - Fixed capacity PV plant (100 subarrays: 10 x 10)
  - Vary separation of subarrays
  - Examine output variability of fleet for a single synthetic day.
- **(2) Compare small, large, and distributed output**

Sandia National Laboratories

Effect of Geographic Diversity(a)



PVCloudSim Model



Parameters: cloud radius = 10 to 100; transmittance = 0.2 to 0.7, cloud coverage = 0.35
(Clouds can overlap)

THANK YOU

Contact Information

Joshua S Stein Ph.D.

Email: jsstein@sandia.gov

Tel: 505-845-0936

Web: http://photovoltaics.sandia.gov/

Sandia National Laboratories